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# Functional status of masticatory system, executive function and episodic memory in older persons

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**SUMMARY** Findings from human experimental studies suggest that mastication positively influences cognitive function. The participants in those studies were relatively young. The goal of this study was to examine the relationship between the functional status of the masticatory system, episodic memory, and executive functions in elderly people. The participants, elderly people living independently at home, were divided into two groups. One group had a full complement of natural teeth ( $n = 19$ ) and the other group had full dentures ( $n = 19$ ). The functional status of the masticatory system was assessed by measuring mandibular excursions (i.e. the distances over which the mandible can move in the open, lateral, and forward directions), bite force, number of occluding pairs and complaints of the masticatory system (facial pain, headaches/migraine). Executive functions and episodic memory

were assessed by neuropsychological tests. Backward regression analysis showed that only in the group of elderly people with full dentures, 22% of executive functions were predicted by complaints of the masticatory system and 19.4% of episodic memory was predicted by masticatory performance (composed of mandibular excursions and bite force). The conclusion of this study is that only in older persons with full dentures the relationship between mastication, episodic memory, and executive function becomes evident when the functional status of the masticatory system decreases.

**KEYWORDS:** masticatory performance, ageing, episodic memory, executive functions, bite force, chewing, elderly people

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A positive relationship between mastication (especially gum chewing) and cognition has been observed in a number of recent human experimental studies. In young adults aged 24–26 years, 3 min of gum chewing was found to improve both spatial working memory and episodic memory (new learning, assessed by Immediate and Delayed Word Recall) relative to sham chewing (chewing with an empty mouth) or no chewing at all (1). A recent study in healthy young adults aged 18–22 years confirmed these findings by showing that there was an improvement in episodic memory while chewing (2).

Result from animal experimental studies, which have recently been carried out into the effects of reduced masticatory performance in middle-aged and elderly

mice, support a positive relationship between chewing and cognition. It was found that the administration of soft food caused a reduction in the synaptic density of the hippocampus, while the removal of molar teeth resulted in a decrease in the number of hippocampal neurons (3, 4). In mice, the administration of soft food or the removal of molar teeth leads to the impairment of spatial learning and spatial working memory. Significantly, the hippocampus is involved in both these cognitive functions (5).

By no means have all human experimental studies conducted in this area found a beneficial relationship between chewing and episodic memory. One recent study investigated healthy young adults (with a mean age of 22.9 years) under the following four conditions:

non-chewing (passive condition), sham chewing, chewing unflavoured gum and chewing gum flavoured with spearmint. In tests of episodic memory, no significant differences were found between participants in the passive condition and those in the other three active conditions (6). In this study, each subject experienced all four of the above-mentioned conditions. Each of these individuals therefore underwent the same neuropsychological tests a total of four times, which means that test-retest effects may well have masked possible positive effects on memory.

Alternatively, variations in the consistency of the gum used in the various studies might account for the discrepancies in the observed effects of chewing on episodic memory (7). This notion was borne out by a functional magnetic resonance imaging (fMRI) study in healthy young adults aged 20–31 years. The study in question found that individuals chewing moderately hard gum exhibited a greater increase in neuronal activity, in the primary sensory motor cortex, operculum and insula than those chewing hard gum (8). In contrast, chewing hard gum was found to increase the neuronal activity in the cerebellum.

The relationship between executive function and chewing has also been examined (2). Executive function is a cognitive function that is an essential prerequisite for independent functioning (9), and one in which the prefrontal cortex is highly involved (10). However, the above study in young adults failed to demonstrate that chewing has any beneficial effects on executive function. That study suffered from the limitation that it used a single test, the Controlled Oral Word Association Test (COWAT), to measure executive function. However, executive function encompasses a whole range of cognitive subfunctions. These include divided attention (when multi-tasking), set-shifting (disengaging attention and re-focusing on a new stimulus), and inhibition (suppressing irrelevant stimuli to focus attention on relevant stimuli) (11).

Taken together, the results obtained from animal studies show a positive relationship between mastication, learning and episodic memory. Studies in humans, however, have failed to demonstrate consistently the existence of a positive relationship between mastication and episodic memory. This inconsistency might be due to methodological shortcomings in some of the studies, as mentioned above, or to the consistency of the chewing gum used. The failure to establish a relationship between mastication and executive function might

be because of the fact that only a single executive function test was used. It is worth noting that, while the relationship between mastication and cognition has been examined in elderly animals, to the best of our knowledge, human studies have been confined to young, healthy adults, without cognitive impairment and elderly females with dementia (12); there has been no study in the healthy elderly. Therefore, it would be particularly interesting to study in non-demented elderly people the relationship between the functional status of the masticatory system, episodic memory, and executive function, as these cognitive functions are vulnerable to the ageing process (13, 14).

The goal of this study was to explore the relationship, if any, between the functional status of the masticatory system, episodic memory, and executive function in two groups of healthy elderly people: one group of healthy elderly people with a full complement of natural teeth and one group of elderly people with full dentures. To examine both groups *separately* is necessary for the following reasons: (1) a degeneration of the hippocampus has been observed in mice in which the molar teeth were removed; (2) previous studies have demonstrated that elderly people with a full complement of natural teeth have a higher level of global cognitive functioning and a higher level of education than those with full dentures (15, 16); and (3) elderly people with a full complement of natural teeth exhibit a greater bite force and larger mandibular excursions (i.e. the distances over which the mandible can move in the open, lateral, and forward directions) than those with full dentures (17). The two groups in this study met these latter two distinctive criteria as will be presented below.

It is hypothesized that in *both* groups the functional status of the masticatory system is positively associated with the performance of tasks that are dependent on both episodic memory and executive function.

## Method

### *Participants*

Older persons with a normal cognitive status who lived independently at home were approached for participation in the study through local advertisements. All those approached agreed to participate. The total number of older persons who participated in the study was 49. Eleven participants appeared to have an

incomplete complement of natural teeth and were subsequently excluded from the study. Nineteen older persons (nine females, 10 males) had a full complement of natural teeth and nineteen older persons (12 females, seven males) had full dentures. Gender did not differ significantly between both groups ( $\chi^2 = 0.96$ , d.f. = 1,  $P = 0.33$ ).

*Level of global cognitive functioning* Level of global cognitive functioning was assessed by means of the Mini-Mental State Examination (MMSE) with a maximum score of 30 (18). Only persons with an MMSE score of 25 or higher, reflecting a normal cognitive status, were included in the study. As expected, the mean MMSE score of the older persons with a full complement of natural teeth was significantly higher than that of older persons with full dentures (for means, standard deviations and *t*-tests, see Table 1).

*Level of education* Level of education was assessed by means of a five-point rating scale: 1 = elementary school not finished; 2 = elementary school finished; 3 = lower secondary school; 4 = higher secondary

school; 5 = higher vocational training for 18+/university. Similar to the MMSE, the level of education of the group of older persons with a full complement of natural teeth was significantly higher than that of the older persons with full dentures (for means, standard deviations and *t*-tests, see Table 1).

*Mandibular excursions and bite force* Larger mandibular excursions and a greater bite force were observed in elderly people with a full complement of natural teeth than those who had full dentures. For details on the assessment of the functional status of the masticatory system, see section Material and Procedure (below). For means, standard deviations and *t*-tests, see Table 2.

*Level of daily physical activity* As epidemiological studies show that the level of daily physical activity has a relationship with the level of cognitive functioning (19). Participants were asked to rate their daily level of activity on a five-point rating scale: 1 = bad, 2 = moderate, 3 = reasonable, 4 = good, 5 = excellent. No significant difference was found between both groups (for means, standard deviations and *t*-tests, see Table 1).

**Table 1.** Means, standard deviations and *t*-tests regarding age, global cognitive functioning by the Mini-Mental State Examination, education, level of activity and level of depression of older persons with a full complement of natural teeth and with full dentures

	Full complement of natural teeth ( <i>n</i> = 19)		Full dentures ( <i>n</i> = 19)		<i>t</i> -tests	
	Mean	s.d.	Mean	s.d.	<i>t</i> (36)	<i>P</i>
Age (range)	73.21 (63–83)	4.28	75.68 (69–82)	3.35	1.99	NS
Mini-Mental State Examination (range)	28.79 (28–30)	0.713	27.79 (25–30)	1.32	2.91	0.006
Level of education	4.11	1.05	3.11	1.05	2.94	0.006
Level of physical activity	3.58	0.69	3.47	0.91	0.40	NS
Beck Depression Inventory	25.47	6.94	24.84	5.42	0.31	NS

**Table 2.** Means, standard deviations and *t*-tests regarding the various components of the functional status of the masticatory system of older persons with a full complement of natural teeth and with full dentures

	Full complement of natural teeth ( <i>n</i> = 19)		Full dentures ( <i>n</i> = 19)		<i>t</i> -tests	
	Mean	s.d.	Mean	s.d.	<i>t</i> (35)	<i>P</i>
Mandibular excursions	85.42	12.68	70.61	11.09	3.77	0.001
Bite force	7.32	3.05	2.89	1.69	5.42	0.001
Masticatory Performance domain*	1.41	1.52	−1.19	1.24	5.76	0.001
Total Pain Intensity	5.26	1.24	5.39	2.17	−0.22	NS
Occluding pairs (range)	11.58 (6–15)	2.76	12.61 (11–14)	1.09	1.48	NS
RDC/TMD	0.21	0.631	0.28	0.461	−0.16	NS

\*Mean *z* scores.

*Depressive symptoms* Patients with a diagnosis of depression were excluded from this study; exclusion of patients with depression was performed by examining the participants' medication carefully by a pharmacist. Nevertheless, *depressive symptoms* could still be present and may show a relationship to both cognitive functioning (20) and pain (21). Therefore, the Beck Depression Inventory (BDI) (22) was administered. The BDI consists of 21 items. The score on each item ranges from 0 to 3, resulting in a maximum score of 63. The BDI scores did not differ significantly between both groups (see Table 1).

*Exclusion criteria* Participants were excluded from the present study if they had vision problems, a history of a psychiatric disorder (e.g. depression), alcoholism, cerebral trauma, hydrocephalus, neoplasm, focal brain disorders, epilepsy, sleep problems (presence of sleep medication) and disturbances of consciousness. None of the approached participants needed to be excluded. The study was approved by the local medical ethical committee.

## Material and procedure

### *Functional status of the masticatory system*

Assessment of the functional status of the masticatory system took place in an active and a passive way. The active assessment included mandibular excursions (size of the excursions and pain intensity) and maximum bite force. Passive assessment of the functional status of the masticatory system included a count of the number of occluding pairs of posterior teeth. Furthermore, a questionnaire aimed at complaints of the masticatory system, face, and head was administered.

### *Active assessment*

*Mandibular excursions.* Active movements of the mandible consisted of: (1) the active vertical maximum mouth opening (with or without pain), expressed in millimetres; and (2) the active horizontal maximum mandibular excursions (left- and right-sided laterotrusions and protrusion), expressed in millimetres. Measurements were performed by means of a plastic dental ruler. This plastic dental ruler is accurate to the nearest millimetre and the reliability of its use in measuring mandibular excursions has been demonstrated in many studies (e.g.

Ref. 23). The vertical movements were corrected for the vertical overbite; protrusion for the horizontal overbite, and the left- and right-sided laterotrusions for the midline deviation. To obtain a total active movement score, the various above-mentioned subscores, expressed in millimetres, were summed. Elderly people with a full complement of natural teeth exhibited larger mandibular excursions than those with full dentures (Table 2).

*Total pain intensity.* As regards pain during mandibular excursions, the subjects were asked to indicate their pain intensity on a five-point Likert scale, ranging from 1 (no pain) to 5 (severe pain). The subjects were also asked to indicate in which area the pain occurred (cheek, temporal area, joint, pre-auricular, floor of the mouth or elsewhere). The total pain intensity score was composed of the pain score during maximum mouth opening, protrusion and laterotrusion (left and right). The total pain intensity score was 20. The total pain intensity score did not differ significantly between both groups (Table 2).

*Bite force.* Maximum bite force was measured by means of a simple disposable gnathometer.\* The subject was instructed to bite as hard as possible on a small plastic mouthpiece, placed between the front teeth of the upper and lower jaws and which was connected to the numerical scale that ranges from 0 to 10. Depending on the bite force, a horizontal slide marker, which is initially at the zero-position, is pushed upward in the direction of the number 10. The maximum score of 10 reflects a bite force of  $\pm 100$  N. Elderly people with a full complement of natural teeth exhibited a greater bite force than those with full dentures (Table 2).

*Masticatory performance domain.* The scores on mandibular excursions and bite force were transformed into z scores and subsequently summed (Cronbach's  $\alpha = 0.75$ ).

### *Passive assessment*

*Occluding pairs.* The subjects were asked to bite a piece of dental modelling wax<sup>†</sup> which is usually used for bite registrations as part of restorative dental procedures. Alminax is a proven bite registration material that is stable at room temperature. This bite registration allows the researcher to count the number of occluding pairs in the posterior region (i.e. the number of pairs of opposing premolars [one occluding pair per premolar

\*Kukident<sup>®</sup>; Procter & Gamble Co., Rotterdam, the Netherlands.

<sup>†</sup>Alminax; Müller & Weygandt, Büdingen, Germany.

possible; maximally two premolars present per dental quadrant] and molars [two occluding pairs per molar possible; maximally three molars present per dental quadrant] that come into contact upon full mouth closure (maximum score: 16) (24). In the present study, the researcher counted the number of occluding pairs of both a full complement of natural teeth and full dentures. Both groups did not differ significantly with respect to occluding pairs (Table 2).

*Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD)* (25) – a Dutch translation (23) was administered. Out of the 31 questions, questions 14, 15, 17, 18 and 19 were applied, as these questions focus particularly on complaints of the masticatory system and the face and on the presence of headaches/migraine (maximum score: 12). Both groups did not differ significantly with respect to the scores on the RDC/TMD (Table 2).

#### *Assessment of executive function and episodic memory*

To assess executive function and memory, various neuropsychological tests were applied. To compose an executive function domain and an episodic memory domain, raw test scores are transformed into *z* scores; the degree of correlation of different *z* scores that are combined into summary scores are calculated by Cronbach's alpha statistics.

#### *Executive function*

*Word Fluency (Category fluency) from the Groninger Intelligence Test (a Dutch intelligence test)* (26). Subjects were asked to name as many animals and professions as possible from each category for 1 min. The test assesses the subjects' ability to retrieve familiar information from semantic memory. The score is the total of correctly named words in both categories.

*Stroop Colour Word Test* (27) was used as a measure of set-shifting and as a measure of interference control, i.e. the subject has to inhibit an automated response. With Stroop Card I, the subject is asked to read aloud as quickly as possible the names of the colours Red, Yellow, Blue and Green which are written in black ink; subsequently, the subject is asked to name the four colours which are randomly presented in small rectangles on Stroop Card II. Finally, Stroop Card III is presented to the subject; on this card the names of the colours are printed in an incongruent ink, e.g. the

colour name red is printed in green ink. The subject is asked to name as quickly as possible the *colour of the ink* and not the word itself. In other words, the subject has to inhibit reading the word. The interference score is computed by subtracting the correctly named colours on the Stroop Card II colour card from the correctly named colours of the ink on the Stroop Card III. A high interference score indicates poor interference control.

*Trailmaking B* (28). This test measures the subjects' visuomotor capacity, i.e. visual scanning, motor speed, and coordination, together with set-shifting and inhibition. In front of the subject is a standard sheet of paper with numbers and letters on it, which are intermingled and circled. The subject is asked to connect with a pencil the numbers and letters in an alternate way, i.e. 1–A–2–B–3–C, etc. as quickly as possible. The score is the time the subject takes to complete the test (seconds).

*Executive function domain.* The raw scores of the Trailmaking B, Word Fluency, and Stroop Card III were transformed into *z* scores and subsequently summed (Cronbach's alpha: 0.69).

#### *Episodic memory*

*Verbal Learning and Memory Test (VLMT)* (29). This test is a Dutch version of the California Verbal Learning Test (CVLT) (30). Sixteen groceries are read aloud by the examiner five times and the subject is instructed to reproduce as many groceries as possible after each presentation, irrespective of the order of presentation. The total number of correctly recalled groceries after five presentations is called the Immediate Recall score (maximum score: 80). After an interval of 15 min, the subjects were asked to recall as many groceries as possible from the previous presented groceries; this score is called the Delayed Recall score (maximum score: 16). Finally, the examiner read aloud a list of 44 groceries among which the 16 groceries presented before and 28 new groceries, in random order. The subjects were asked to recognize as many words as possible from the list presented previously (subtest Recognition). The score is the total number of correctly recognized items minus the total number of incorrectly recognized items (maximum score: 44).

*Episodic memory domain.* The memory domain consisted of the summation of the *z* scores of the subtests Immediate Recall and Delayed Recall (Cronbach's  $\alpha = 0.84$ ) as adding the subtest Recognition lowered the Cronbach's alpha to 0.77.

### Data analyses

As expected, both groups showed significant differences regarding MMSE scores and education. In addition, important parts of the functional status of the masticatory system such as mandibular excursions and bite force (domain Masticatory Performance) appeared to differ between the two groups. Therefore, it is interesting to present for each group separately, by means of Pearson's correlations, and by means of Spearman correlations when the data were not normally distributed, the relationships between the components of the functional status of the masticatory system and demographic variables, between the components of the functional status of the masticatory system themselves, and between the components of the functional status of the masticatory system, the executive function domain, and the episodic memory domain. In view of multiple correlations, a Bonferroni correction was applied, resulting in a value of  $P < 0.005$  to be significant. These relationships will be presented first.

Subsequently, the data of both groups were included into one backward multiple regression analysis, with the Episodic memory and Executive function domain as dependent variables and MMSE and Education as independent variables to control possible confounding effects. Other independent variables included Group  $\times$  Masticatory Performance, Group  $\times$  RDC/TMD, MMSE, Education, Masticatory performance and RDC/TMD. We inserted Group as a dummy variable into the regression equation: Group 'older persons with a full complement of natural teeth' = 0 and Group 'older persons with full dentures' = 1. For variables to be included in the backward multiple regression analysis,  $P < 0.05$  was used; for variables to be excluded from the backward multiple regression analysis,  $P > 0.10$  was used. Cohen's  $f^2$  effect sizes were calculated;  $f^2$  effect sizes of 0.02, 0.15 and 0.35 are considered small, medium and large respectively (31). The SPSS-PC program was used for data analyses (32).

## Results

### *Executive function and episodic memory in older persons with a full complement of natural teeth compared to executive function and episodic memory in those with full dentures*

Regarding the Executive function domain, older persons with a full complement of natural teeth (mean

1.01, s.d. = 4.09) did not differ significantly from older persons with full dentures (mean 0.41, s.d. 3.03) [ $F(1,35) = 0.258$ ;  $P = 0.615$ ]. Similar findings were observed regarding the Episodic memory domain: the former group (mean 0.69, s.d. 3.33) did not differ significantly from the latter group (mean 0.25, s.d. 2.93) ( $F(1,35) = 0.184$ ,  $P = 0.671$ ).

*Relationships between the functional status of the masticatory system and demographic variables, between the components of the functional status of the masticatory system themselves, and between the functional status of the masticatory system, the executive function domain, and the episodic memory domain, for each group separately.*

*Older persons with a full complement of natural teeth Relationship between components of the functional status of the masticatory system and demographic variables and between the components of the functional status of the masticatory system themselves.* Data analysis showed a significant positive correlation between education and occluding pairs. As expected, the correlation between Masticatory Performance domain, bite force and Mandibular Excursions was significant (Table 3).

*Relationship between components of the functional status of the masticatory system and the executive function domain.* The correlations between the various components of the functional status of the masticatory system and the executive function domain were not significant (Table 3).

*Relationship between components of the functional status of the masticatory system and the episodic memory domain.* No significant correlations between the various components of the functional status of the masticatory system and the episodic memory domain were observed (Table 3).

*Older persons with full dentures Relationship between components of the functional status of the masticatory system and demographic variables and between the components of the functional status of the masticatory system themselves.* Besides the expected significant positive correlations between Masticatory Performance domain, bite force, and Mandibular Excursions, no significant correlations between the various components of the functional status of the masticatory system themselves and between the various components of the functional status of the masticatory system and demographic variables were observed (Table 4).

**Table 3.** Pearson correlations between demographic variables, global cognitive functioning (MMSE: Mini-Mental State Examination), components of the functional status of the masticatory system, episodic memory (Mem.) and executive function (Exc. funct.), in older persons with a full complement of natural teeth

	Full complement of natural teeth										
	Age	Educ	MMSE	Mand. excur.	Pain int.	Bite force	Occl. pairs	RDC/TMD	Mem.	Exec. funct	Mast. Perf.
Age	–										
Educ. <sup>s</sup>	–0.126	–									
MMSE	0.034	0.106	–								
Mand. excur.	–0.249	0.195	–0.088	–							
Pain int. <sup>s</sup>	–0.221	0.186	0.143	0.315	–						
Bite Force <sup>s</sup>	–0.208	0.228	0.055	0.314	0.030	–					
Occl. pairs <sup>s</sup>	0.266	0.743*	–0.089	0.271	0.280	0.13	–				
RDC/TMD	–0.110	0.076	0.003	–0.008	0.291	–0.465	0.092	–			
Mem.	–0.182	0.144	0.085	–0.029	–0.197	0.154	0.084	–0.032	–		
Exec. funct.	–0.428	0.174	0.173	0.391	0.134	0.137	0.233	–0.11	0.137	–	
Mast. Perf.	–0.239	0.182	–0.067	0.789*	0.155	0.823*	0.224	–0.339	0.026	0.287	–

s, Spearman correlations; Educ, education; Mand. Excur., mandibular excursions; Pain int., pain intensity; Occl. pairs, occlusal pairs; RDC/TMD, Research Diagnostic Criteria for Temporomandibular Disorders; Mast. Perf., masticatory Performance. \* $P < 0.005$ .

**Table 4.** Pearson correlations between demographic variables, global cognitive functioning (MMSE: Mini-Mental State Examination), components of the functional status of the masticatory system, episodic memory (Mem.) and executive function (Exec. Funct.), in older persons with full dentures

	Full dentures										
	Age	Educ.	MMSE	Mand. excur.	Pain int.	Bite force	Occl. pairs	RDC/TMD	Mem	Exec. funct.	Mast. Perf.
Age	–										
Educ. <sup>s</sup>	–0.350	–									
MMSE	–0.150	0.105	–								
Mand. excur.	0.088	–0.332	–0.052	–							
Pain int. <sup>s</sup>	–0.005	–0.273	0.254	–0.074	–						
Bite force <sup>s</sup>	0.270	–0.321	0.195	0.723*	–0.028	–					
Occl. pairs <sup>s</sup>	0.262	0.084	0.232	0.241	–0.563	0.354	–				
RDC/TMD	–0.326	–0.148	0.188	–0.110	0.124	0.473	0.222	–			
Mem.	0.205	–0.107	–0.060	0.392	–0.394	0.661*	0.553	–0.026	–		
Exec. funct.	–0.190	0.129	0.131	0.245	–0.108	0.329	0.459	–0.656*	–0.070	–	
Mast. Perf.	0.234	–0.393	0.036	0.936*	–0.030	0.874*	0.294	–0.352	0.565	0.395	–

s, Spearman correlations; Educ, education; Mand. excur., mandibular excursions; Pain int., pain intensity; Occl. pairs, occlusal pairs; RDC/TMD: Research Diagnostic Criteria for Temporomandibular Disorders; Mast. Perf., Masticatory Performance. \* $P < 0.005$ .

*Relationship between components of the functional status of the masticatory system and the executive function domain.* A significant negative correlation between RCD/TMD and Executive functions was observed (Table 4).

*Relationship between components of the functional status of the masticatory system and the episodic memory domain.*

The positive correlation between bite force and the Episodic Memory domain was significant (see Table 4).

*Backward regression analysis including both groups* The dependent variables to be predicted were the Executive function domain and the Episodic memory domain.



The regression equations reported below (Executive functions domain and Episodic memory domain) are the best fit models that emerged from the backward stepping process.

*Executive functions domain* The standardized multiple regression equation for predicting the Executive functions domain is:

$$\begin{aligned} \text{Predicted ZExecutive functions domain} \\ = +0.112\text{ZRDC/TMD} - 0.137\text{ZGroup} \\ - 0.515\text{ZGr\_RDC/TMD} \end{aligned}$$

The multiple correlation between the Executive functions domain, RDC/TMP, Group, and the interaction between Group  $\times$  RDC/TMD was significant ( $r^2 = 0.221$ ) [ $F(3,34) = 3.21$ ,  $P = 0.035$ ]. The results show that the multiple correlation accounted for 22% of the variance of the Executive functions domain. The effect size Cohen's  $f^2$  was 0.28 which is moderate to large (31).

As regards the independent variables in the model only the interaction between Group and RDC/TMD showed a significant effect on Executive functions ( $t = 2.489$ ,  $P = 0.018$ ).

*Post hoc* tests revealed the following results within each group. Within the group of older persons with a full complement of natural teeth, the relationship between RDC/TMD and Executive functions was not significant [standardized  $\beta = -0.11$ ,  $t(17) = -0.47$ ,  $P = 0.65$ ]. By contrast, within the group of older persons with full dentures a significant relationship was observed between RDC/TMD and Executive functions (standardized  $\beta = 0.656$ ) [ $t(17) = 3.58$ ,  $P = 0.002$ ].

*Episodic memory domain* The standardized multiple regression equation for predicting the Episodic memory domain is:

$$\begin{aligned} \text{Predicted ZEpisodic memory domain} \\ = +0.03\text{ZMasticatory Performance} + 0.158\text{ZGroup} \\ + 0.490\text{ZGr\_Masticatory Performance} \end{aligned}$$

The multiple correlation between the Episodic memory domain, Masticatory Performance, Group, and the interaction between Group  $\times$  Masticatory Performance was nearly significant ( $r^2 = 0.194$ ) [ $F(3,34) = 2.73$ ,  $P = 0.059$ ]. The results show that the multiple correlation accounted for 19% of the variance of the Episodic Memory domain.

Although the model was not statistically significant, due to the number of independent variables in combination with a relatively small sample size of 38, the effect size Cohen's  $f^2$  was 0.24 which is moderate to large (31). On the basis of this effect size, and taking the explorative character of the study into consideration, we felt it was justified to further interpret the above mentioned model. As regards the independent variables in the model, only the interaction between Group and Masticatory Performance showed a nearly significant effect on Episodic Memory [ $t(17) = 2.021$ ,  $P = 0.051$ ].

*Post hoc* tests revealed the following results within each group. Within older persons with a full complement of natural teeth, the relationship between Masticatory Performance and the Episodic memory domain did not appear to be significant [standardized  $\beta = 0.026$ ,  $t(17) = 1.05$ ,  $P = 0.92$ ]. However, the relationship between Masticatory Performance and the Episodic memory domain within the group of older persons with full dentures was significant [standardized  $\beta = 0.565$ ,  $t(17) = 2.83$ ,  $P = 0.012$ ].

## Discussion

First, the relationships between the various components of the functional status of the masticatory system, between the various components of the masticatory system and demographic variables (age, education, MMSE), and between the various components of the masticatory system, executive functions, and episodic memory were examined within a group of older persons with a full complement of natural teeth and within those who had full dentures. Analysing data in two separate groups was justified because as expected, the former group had a higher level of global cognitive functioning, a higher level of education, greater bite force, and larger mandibular excursions.

Subsequently, *both* groups were included into a backward multiple regression analysis to examine whether the Episodic memory domain and the Executive functions domain could be predicted by one or more components of the functional status of the masticatory system. However, these findings should be considered with caution as the number of participants is relatively small for regression analysis. Therefore, we plan to replicate the study with a much larger group of participants.

*Relationship between the functional status of the masticatory system, demographic variables, Executive functions and Episodic memory within each group separately*

*Relationship between the components of the functional status of the masticatory system* Both the group of people with a full complement of natural teeth and the group of people with full dentures exhibited no significant correlations between the various components of the functional status of the masticatory system.

*Relationships between the functional status of the masticatory system, and demographic variables* Within the group of elderly people with a full complement of natural teeth there were no significant correlations between the functional status of the masticatory system, age and MMSE. The same was true of the group of elderly people with full dentures. The significant positive correlation between occluding pairs and level of education in the former group parallels the previous finding of a relationship between missing teeth and level of education (33).

The fact that there was no significant correlation between occluding pairs and level of education in elderly people with full dentures requires an explanation. It might be that, compared to the number of occluding pairs seen in elderly people with a full complement of natural teeth, the number of occluding pairs within the former group showed much less variation (Table 2). This would indeed be consistent with the use of full dentures.

*Relationship between the components of the functional status of the masticatory system and the Executive functions domain* The results of the present study show a significant negative relationship between the Executive functions domain and only one component of the functional status of the masticatory system, i.e. RDC/TMD, exclusively in the group of elderly people with full dentures. This finding implies that the more extensive the complaints of the masticatory system/face/headaches/migraine, the worse the performance of tests appealing to the Executive functions domain. It should be noted that the RDC/TMD questionnaire is a 'hybrid' instrument that was composed by its developers of many small parts of other, already existing instruments (for a detailed description, see Ref. 25).

This finding is in line with the results from a fMRI study that suggest that chewing might provoke

increased neuronal activity in the prefrontal cortex (PFC), particularly in elderly subjects (34). The PFC is known to play a crucial role in executive function (10). In contrast, another previous study failed to find a relationship between chewing and executive function in young adults. However, that study did not examine the various components of the functional status of the masticatory system and used only a single test to assess executive function (2) whereas the present study used three tests for this purpose. Furthermore, the latter tests assess different aspects of executive function such as divided attention, set-shifting, and inhibition (35–37).

It is noteworthy that a significant relationship between the functional status of the masticatory system, i.e. RDC/TMD and the Executive functions domain has not only been observed when analysing the scores of each group separately; including both groups into a backward regression analysis yielded the same outcome, as will be discussed below.

Finally, the PFC is functionally related to the hippocampus (5) and the cerebellum (38), and this relationship plays a crucial role in episodic memory (39, 40). In this line of reasoning, it is important to note that executive functions are a prerequisite for episodic memory (41). Moreover, it has been demonstrated in an fMRI study that as a compensatory mechanism older persons show a higher activity in the PFC than younger persons when performing a memory task as good as possible (42). In other words, a relationship between the functional status of the masticatory system and the Episodic memory domain, as will be addressed next, might also imply an involvement of the PFC.

*Relationship between components of the functional status of the masticatory system and the Episodic memory domain* One noteworthy result was the significant correlation between the bite force, a component of the Masticatory performance domain, and the Episodic Memory domain found in the group of elderly people with full dentures. A relationship between chewing efficiency, which is strongly associated with bite force (43), and episodic memory has previously been observed in studies with young adults (1, 2). No significant correlations between the components of the functional status of the masticatory system and the Episodic memory domain were observed in the group of older persons with a full complement of natural teeth. This discrepancy in results will be addressed in the next section.

*Predicting Executive functions and Episodic memory by one or more components of the functional status of the masticatory system*

The results of a backward multiple regression analysis including *both* groups showed that RDC/TMD predicted executive functions particularly in the group of older persons with full dentures. This result indicates that the lesser the discomfort associated with the masticatory system (RDC/TMD), and thus the better the functional status of the masticatory system, the better the performance of tests for executive functions. Remarkably, this finding did not occur in the older persons with a full complement of natural teeth. Another finding was the prediction of Episodic memory by the interaction between Group and Masticatory Performance, implying that the better the masticatory performance, the better the performance of episodic memory tests. Again, this latter finding was only observed in the group of older persons with full dentures.

An interesting question that arises is as to why, in contrast to our expectation, such relationships were not observed within the group of elderly people with a full complement of natural teeth. Both groups did not differ with respect to the level of daily physical activity, a factor that might influence cognitive functioning (44). Older persons with a full complement of natural teeth did have a higher level of education though. This is known to contribute to the efficiency of a neuronal cognitive network, thereby decreasing the risk of cognitive impairment (45). Alternatively, apart from having a higher level of education, this group of elderly people also differed from the second group in other ways. They had a higher level of global cognitive functioning, were able to exert a greater bite force, and had larger mandibular excursions. We suggest that all of these factors *together* may contribute to the enrichment of the environment. Enriched environment which also includes sensory motor activity has a known beneficial influence on brain plasticity, even in old age (46). However, the moment one important aspect of enriched environment, i.e. sensory motor activity, declines, in this study a reduction in mastication, the relationship between mastication and cognition becomes more prominent. This argument is supported by a study in which a decline in physical activity, more specifically a *decrease* in gait speed, was associated with a decline in cognitive functioning (47). Indeed, a reduction in sensory motor activity and thus in enriched

environment may have a negative effect on brain functioning (48). A comparison between the functional status of the masticatory system and walking is justified, as chewing also boosts the heart rate (49) resulting in an increase in cerebral blood flow in the fronto-temporal areas (50). These areas play an essential role in episodic memory and executive function (51, 52).

*Future research involving older persons with and without dementia* The aim of the present study was to examine the relationship between the functional status of the masticatory system, executive function and episodic memory in healthy elderly people without cognitive impairment. To examine the influence of age on the relationship between chewing and cognition, the cognitive functioning of young people should be compared with that of the older people, both groups including those with a full complement of natural teeth and those with full dentures.

Age is also the highest risk factor for dementia (53). To the best of our knowledge, only one study has examined the relationship between cognition, the number of teeth, maximum bite force, occlusal contact area, and mastication in elderly females with dementia (12). The results revealed that cognitively impaired subjects showed a significant decrease in maximum bite force, occlusal contact area and mastication scores. One of the limitations of that study was that cognition was only assessed by a Japanese screening instrument which is similar to the Mini-Mental State Examination (18). Another impediment was that details of both the aetiology and the stage of the dementia remained obscure. Finally, this study suffered from the constraint that the mastication score was obtained using a questionnaire which required the participants to work through a list of 35 different food items. In each case, they were asked to indicate whether they were able to chew the food in question. Accordingly, it would be interesting to examine the relationship between mastication, executive function and episodic memory in a study involving elderly cognitively impaired people which controls for the above-mentioned limitations.

If a replication of the present study with a larger group of participants and a study with older persons with dementia confirm a relationship between mastication and cognitive functioning in those with full dentures, a next step might be to examine whether chewing *as an intervention* might improve or stabilize

cognitive functioning, first in older persons without dementia and subsequently in those with dementia. The rationale underlying this somewhat premature suggestion for future research is as follows. The PFC, the hippocampus, and the cerebellum all show an age-related decline (14, 54–56). Moreover, the PFC and the hippocampus are affected by the most prevalent subtypes of dementia such as Alzheimer's disease, vascular dementia, and frontotemporal dementia (57–62). This deregulates the functional neural circuits, which damages executive function and episodic memory. Various types of physical activity, such as brisk walking, have been shown to be effective in improving cognitive functioning in healthy elderly people (63), in those with Mild Cognitive Impairment (64) and in those with dementia (44). Alternatively, for those who are no longer able to walk, chewing could be a means of activating the neuronal circuits that are involved in executive functions and episodic memory.

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